Predictions of hadron abundances in pp collisions at the LHC

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Based on the statistical hadronization model, we obtain quantitative predictions for the relative abundances of hadron species in pp collisions at the LHC. By using the parameters of the model determined at $\sqrt{s} = 200$ GeV, and extrapolating the overall normalization from $p\bar{p}$ collisions at the SPS and Tevatron, we find that the expected rapidity densities are almost grand-canonical. Therefore, at LHC the ratios between different species become essentially energy-independent, provided that the hadronization temperature T_H and the strangeness suppression factor γ_S retain the stable values observed in the presently explored range of pp and $p\bar{p}$ collisions.

Just before the advent of data from the highest energy hadron collider of all times, the LHC, we want to ask what, if anything, we can predict quantitatively for the forthcoming measurements dealing with the truly non-perturbative strong interaction regime. The one feature which has emerged over the years in multihadron production, from e^+e^- annihilation to heavy ion collisions, is its statistical nature. The relative abundances of the different species are predicted with remarkable precision by an ideal resonance gas model, with a hadronization temperature converging to about 170 MeV in the limit of high collision energy [1–5], and this feature has already been used to make predictions for relative hadron abundances expected at the LHC in Pb-Pb collisions [6, 7].

The only aspect which distinguishes elementary from nuclear collisions is the rate of strangeness production, which in elementary collisions is suppressed by a universal factor $\gamma_S \simeq 0.6$, while in heavy ion collisions $\gamma_S \to 1$. The origin of γ_S has been discussed in various approaches; so far, there does not seem to exist a satisfactory explanation of its value in elementary collisions. We will therefore treat it as a parameter to be determined empirically, and use the appearent convergence to an energy-dependent value $\gamma_s \simeq 0.6$ in pp interactions [2, 3] as input for our predictions. In this respect, our predictions for pp collisions differ from those of ref. [7], where the extra strangeness suppression is implemented through the introduction of a strangeness correlation volume[1]. However, we will consider as well $\gamma_S \simeq 1$ as the other "extreme". Clearly this issue is the most interesting in the analysis of the forthcoming pp data.

The statistical model to be used is described in detail in ref. [2]. We repeat here only essential points and caveats for its specific application to LHC experiments. The simple analytical formulae for multiplicities derived within the statistical model (see e.g. [4]) apply in principle to full phase space multiplicities, since possible charge-momentum correlations are integrated out. Therefore, in order to apply the same formulae to midrapidity data, one has to assume that particle ratios there are essentially the same as those in full phase space. While such an assumption is certainly not tenable at low collision energy, it is expected to become valid in sufficiently high energy collisions with large rapidity coverage. We thus assume that the primary rapidity density of each species in pp collisions is given by (see e.g. [3, 8]):

$$\left\langle \frac{dn_j}{dy} \right\rangle_{y=0}^{\text{primary}} = \frac{AVT(2J_j + 1)}{2\pi^2} \sum_{n=1}^{\infty} \gamma_S^{N_s n} (\mp 1)^{n+1} \frac{m_j^2}{n} K_2 \left(\frac{n m_j}{T} \right) \frac{Z(\mathbf{Q} - n\mathbf{q}_j)}{Z(\mathbf{Q})}, \tag{1}$$

where A is a common normalization factor taking into account the ratio of production in the midrapidity interval to the overall rate; V is a volume (see discussion below), T is the temperature, $Z(\mathbf{Q})$

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[1] Unlike γ_S, this mechanism does not suppress hidden strange meson production; hence the two approaches give different quantitative predictions for the ϕ meson yield.

is the canonical partition function depending on the initial abelian charges $\mathbf{Q} = (Q, N, S, C, B)$, i.e., electric charge, baryon number, strangeness, charm and beauty, respectively; m_j and J_j are the mass and the spin of the hadron j, and $\mathbf{q}_j = (Q_j, N_j, S_j, C_j, B_j)$ its corresponding charges; γ_S is the extra phenomenological factor implementing a suppression of hadrons containing N_s strange valence quarks. In the formula (1), the upper sign applies to bosons and the lower sign to fermions. For temperature values of 160 MeV or higher, Boltzmann statistics corresponding to the term $n = 1$ only in the series (1) is a very good approximation for all hadrons (within 1.5%) but pions. For resonances, the formula (1) is folded with a relativistic Breit-Wigner distribution of the mass m_j. To the above primary production one has to add the secondary production due to the strong and electromagnetic decay chains. In our calculation, we include all known resonances up to mass of 1.8 GeV, as well as baryon resonances of Λ-, Δ- and Ξ-type between 1.8 and 1.92 GeV. Also, it is assumed that these decays do not distort noticeably the rapidity distributions.

In formula (1), the volume V appears both as an overall multiplicative factor and in the chemical factors $Z(\mathbf{Q} - n\mathbf{q}_j)/Z(\mathbf{Q})$ (related to the so-called canonical suppression phenomenon). It thus contributes to the determination of the *ratios* of different particle species and cannot be absorbed into an overall normalization factor AV. We note that this volume, determined by fitting measured rapidity densities to the formula (1), has no direct physical meaning. In fact, it corresponds to the volume a cluster would have if its fully integrated hadronic multiplicities were proportional to the measured midrapidity densities. Only if one uses experimental 4π multiplicities does the fitted volume have a more direct physical meaning; in the global cluster scheme [2], it gives the sum of the volumes of the actually produced clusters, for pointlike hadrons.

The volume factor determined at $\sqrt{s} = 200$ GeV is $VT^3 = 135 \pm 60$ [4]; it is obtained from an analysis of midrapidity densities measured at RHIC; hence the large error. In order to extrapolate it to LHC energy, we assume that its value evolves with energy the same way as midrapidity densities. This requires that T stays constant, for which we have strong evidence, as already mentioned. By using five $\mathrm{d}n/\mathrm{d}\eta$ values measured for charged particles at SPS and Tevatron at energies 200, 546, 630, 900 and 1800 GeV in $p\bar{p}$ collisions [9], we found that this evolution is best fitted with a polynomial in $\log \sqrt{s}$:

$$\frac{\mathrm{d}n_{\mathrm{ch}}}{\mathrm{d}\eta} = 1.35 + 0.0375 \log \sqrt{s} + 0.00962 \log^2 \sqrt{s} + 0.00434 \log^3 \sqrt{s}, \tag{2}$$

with $\sqrt{s}$ in GeV. With the above coefficients, and renormalizing the right hand side so as to obtain $VT^3 = 135$ at $\sqrt{s} = 200$ GeV, we are able to estimate the VT^3 parameter at larger energies. For instance, at $\sqrt{s} = 10$ TeV, the predicted value becomes $VT^3 = 323$.

Here a comment is in order. The parameter VT^3 was determined with a large error in the statistical model analysis of the RHIC data, because it is strongly anticorrelated to the temperature. Both T and VT^3 contribute to determine the canonical weight factors in formula (1), but the final uncertainty of the weights, as determined from fit errors, is much smaller than that of VT^3, because of its anticorrelation to T. Moreover, the canonical weights have another important feature: for large volumes and fixed, finite charges, they saturate to their grand-canonical limit 1, so that the relevant uncertainties naturally decrease as the energy, and hence the system size, is increased. This is precisely the case for LHC, where, at least for midrapidity densities, the grand-canonical limit seems to be almost attained, as we will shortly see.

In table I, we provide predictions for the ratios between midrapidity densities of several species and that of charged particles for a temperature value $T = 170$ MeV, using the extrapolated value of $VT^3 (= 323)$ parameter at $\sqrt{s} = 10$ TeV, and $\gamma_S = 0.6$ and $\gamma_S = 1$. It can be seen that the difference between particle and antiparticle yields is small and not larger than 10%. This is a manifestation of the proximity of the chemical factors (with special regard to baryon number) to their asymptotic value 1 and it implies that the numbers in table I are stable against a variation of centre-of-mass energy within the typical LHC range, from 1 TeV onwards. Therefore, in this energy region, the main source of error on model predictions is the uncertainty on the parameters T and γ_S, whose values are an educated guess based on those determined at $\sqrt{s} = 200$ GeV [4] and the very mild increasing trend observed for γ_S [2]. The uncertainties can be reasonably estimated to be of the order of 3% for the temperature and 8% for γ_S which are reflected into an error on the ratios quoted in the left column of table I depending on particle species, ranging from few percents for pions up to 20% for ϕ and 40% for Ω, which is the worst case.

In table II, we provide the same set of predictions for a temperature value $T = 170$ MeV and $\gamma_S = 0.6$ and $\gamma_S = 1$, but in the fully grand-canonical formalism, i.e. for the infinite energy limit. It can be seen

Particle	$(dn/dy)/(dn/dy_{\rm ch})$ $\gamma_S = 0.6$	$(dn/dy)/(dn/dy_{\rm ch})$ $\gamma_S = 1$
π^0	0.463	0.442
π^+	0.415	0.392
π^-	0.412	0.389
K^+	0.0483	0.0703
K^-	0.0474	0.0691
K^0_S	0.0471	0.0681
η	0.0499	0.0526
ρ^0	0.0565	0.0508
ρ^+	0.0561	0.0500
ρ^-	0.0555	0.0496
ω	0.0508	0.0449
η'	0.0497	0.0457
ϕ	0.00379	0.00908
p	0.0334	0.0294
$\bar{p}$	0.0303	0.0271
Λ	0.0115	0.0165
$\bar{\Lambda}$	0.0107	0.0156
Ξ^-	0.00104	0.00254
$\bar{\Xi}^+$	0.000995	0.00245
Ω^-	0.000115	0.000474
$\bar{\Omega}^+$	0.000111	0.000464

TABLE I: Predictions of the midrapidity density of hadrons relative to that of all charged hadrons at $\sqrt{s} = 10$ TeV, using an extrapolated energy dependence and assuming a hadronization temperature $T = 170$ MeV. The quoted rates *do not* include weak decay products.

that the difference with respect to previous case is in most cases very small, and it is also well within the estimated theoretical uncertainty of our main calculation shown in table I. This indicates that the LHC is expected to provide hadron abundances corresponding almost to the infinite energy limit. It is perhaps worthwhile to emphasize this point in more detail. Hadronization of strongly-interacting system does not depend on its initial energy density, and hence not on the initial collision energy. Thus the validity of the given predictions for relative abundances does not depend on the functional energy dependence of the overall hadron multiplicity. At lower collision energy, in the statistical hadronization model, an energy-dependence of relative abundances enters through the conservation laws of inner charges (and possible variation of γ_S). When these saturate to the grand-canonical limit at high energies, the predictions of relative abundances are those of asymptotically stable thermodynamics.

Finally, since at the LHC the production cross-section of $c\bar{c}$ pairs is predicted to be of the order of few mb, we have checked the stability of the above predictions against the introduction of heavy flavoured hadron contribution. We have then estimated the same ratios by assuming 30% of events with $c\bar{c}$ production and found that the differences with respect to the no-$c\bar{c}$ case are of the order of a percent or less.

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Particle	$(dn/dy)/(dn/dy_\mathrm{ch})$ $\gamma_S = 0.6$	$(dn/dy)/(dn/dy_\mathrm{ch})$ $\gamma_S = 1$
π^0	0.462	0.441
$\pi^+ = \pi^-$	0.413	0.390
$K^+ = K^-$	0.0480	0.0698
K_S^0	0.0473	0.0682
η	0.0497	0.0524
ρ^0	0.0563	0.0506
$\rho^+ = \rho^-$	0.0557	0.0497
ω	0.0505	0.0477
η'	0.00375	0.00455
ϕ	0.00377	0.00903
$p = \bar{p}$	0.0321	0.0285
$\Lambda = \bar{\Lambda}$	0.0112	0.0162
$\Xi^+ = \Xi^-$	0.00105	0.00254
$\Omega^+ = \Omega^-$	0.000121	0.000488

TABLE II: Predictions of the midrapidity density of hadrons relative to that of all charged hadrons at $\sqrt{s} = 10$ TeV in the grand-canonical limit. The temperature value is assumed as $T = 170$ MeV, and the numbers *do not* include weak decay products.

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